Sensor-Based Interactive Worksheets to Support Guided Scientific Inquiry

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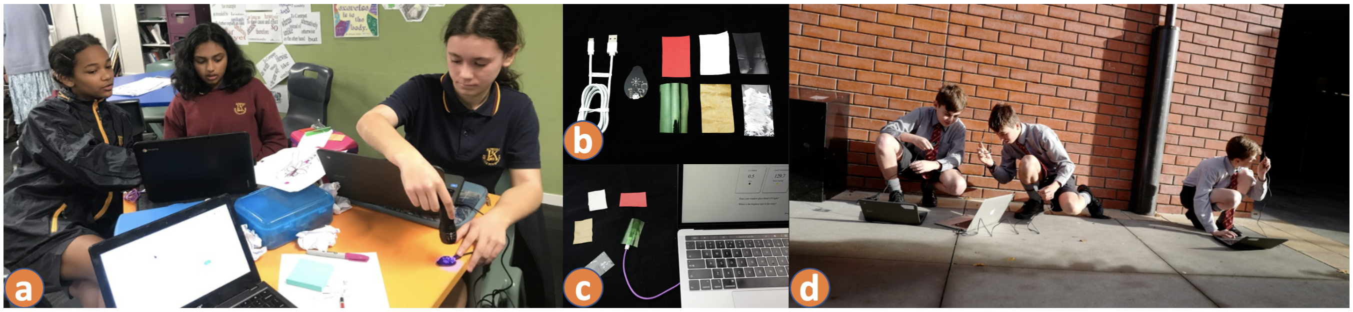

Figure 1: (a) Students engage in a guided experiment using our interactive worksheets; (b) Measurement setup that includes various light filtering materials and a UV sensor; (c) Different materials that were tested; (d) Students engage in free exploration.

ABSTRACT

Scientific inquiry involves prediction, observation and explanation (POE) of phenomena and data. Appropriate guidance through these steps is essential for helping students learn and form positive attitudes towards science. Sensor-based education toolkits are becoming a popular way to provide this guidance, but they typically present different interfaces for measurement and learning materials which places a high cognitive demand on learners. To address this challenge, we developed a web application to integrate the scientific inquiry method where students are guided step-by-step, using a scaffolded-learning approach, through slide-based worksheets that provide direct interaction with real-time sensor measurements. We evaluate this approach through a qualitative analysis of data collected from two field studies in classrooms with a total of 42 students. We show that our approach encouraged positivity and further learning in science. Students displayed and expressed interest to conduct science experiments outside of class. We identify design implications for seamless learning, storytelling and integration of POE guided scientific inquiry with sensor-based toolkits.

CCS CONCEPTS

• **Applied computing → Interactive learning environments**.

KEYWORDS

Science education, scientific inquiry, sensor integration, toolkit, open-source, learning scenario

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1 INTRODUCTION

The importance of early science education in enabling economic growth and social development in the information age is widely recognised [9, 11]. Scientific inquiry, as a popular student-centred educational method, has been shown to help students develop positive attitudes towards science while enabling them to learn effectively [8]. One of the main reasons for using scientific inquiry in schools is to bring science education closer to the authentic practices of the scientific community [15].

In order for students to learn about scientific inquiry effectively, appropriate guidance is necessary [13, 16, 21]. An increasingly common way of providing this guidance is through the use of Technology-Enhanced Learning (TEL) science education toolkits. These are typically designed to scaffold students through collecting data, conducting experiments, and engaging in scientific inquiry across a range of topics within the natural sciences. Existing toolkits offer collections of ready-to-use lessons and projects [5, 27], some of which make use of sensor-enriched devices or dedicated sensor platforms. A few use widely-available devices like smartphones as portable data collection and analysis platforms [12, 24] while others provide dedicated hardware for data collection and accompanying analysis software [10, 29].

However, TEL toolkits often consist of two disparate components. One part is the learning material, which can include a motivational story, instructions for conducting an experiment, interpretation guidelines for the experiment's data, and other multimedia content. The other part is the sensor system for the collection of experiment data. In general, the media on which the instructions are provided (an electronic or printed hand-out) is different from the media that is used to collect the measurements (such as a smartphone application or a proprietary measurement apparatus). Thus, when conducting an experiment with a sensor platform, students have to switch from the instructional content to the measurement interface. This change of media splits learners' attention and increases the load on working memory, diverting attention away from the actual lesson to be learned [22, 30]. In Multimedia Learning Theory [23], this is described as the Coherence Effect. Reducing extraneous cognitive load by removing the need for learners to mentally integrate the information sources may therefore improve the learning experience [32]. As such, our work was aimed at addressing the following central research question:

How do children interact with a guided scientific inquiry lesson that integrates learning material directly with real-time sensor measurements?

To investigate this, we developed a web application which supports guided scientific inquiry through interactive worksheets that are enriched by sensor-based interactions. We make the following contributions to the field of Technology-Enhanced learning: 1) the development of a platform with interactive worksheets for conducting sensor-based scientific inquiries; and 2) a field-study evaluation of our approach with 42 students, to understand how the interactive worksheets impact the way that students view a science inquiry lesson.

2 RELATED WORK

2.1 Interactive Tools for Supporting Scientific Inquiry

Various interaction techniques, especially for TEL [2], have been developed and evaluated with respect to Cognitive Load Theory (CLT) [14, 30], which posits that cognitive load during a learning task should be minimised.

Zydeco [17] is a system that allows students to perform scientific inquiry in a museum using a mobile device. In Zydeco, students are first asked to choose the role of a 'Paleontologist', 'Paleobotanist', or 'Meteorologist'. Based on the selected role, Zydeco provides a list of recommended exhibits in the museum, from which students can collect data to investigate their hypotheses. Different roles receive different hints over the course of the visit, which can motivate a group of students to collaborate and share their ideas. Students can take pictures and record audio notes as supporting material when they present their findings to peers. Since there is no learning material included within Zydeco, students must receive their formal instruction independent of the platform.

The Next Experiment Toolkit (NexP) [20] is a toolkit for designing and running controlled experiments. With a scaffolded interaction flow, NexP walks users through the five steps of designing a controlled experiment [19]. To carry out the experiment, NexP allows for the execution of custom code that presents trials and records participants' performances. While NexP helps students understand the scientific inquiry process, it does not include any direct integration with sensor data.

2.2 Science Education Toolkits

Numerous tool-kits integrate sensor measurements into teaching lessons. Smartphone-based tool-kits provide apps for recording, organising, and visualising sensor data in real-time. They even support note-taking and the sharing of findings with others, functions which are classically supported by pen-and-paper notebooks. Lab4Physics [24] supports the collection and visualisation of data from a smartphone's sensors. It features an oscilloscope-like graphing display for data collection. Although the integration into the lesson is seamless, its interaction is limited to displaying live sensor data. In contrast, Google's Science Journal [12] helps users to conduct experiments by recording sensor data and providing functions for note-taking and results sharing. The app is standalone but often integrated into science lessons [5]. Smartphone-based toolkits are easily-available and deployable, allowing students to use their personal smartphones to conduct their own experiments. However, typical available sensors (e.g. accelerometer, microphone, GPS) do not support the measurement of even simple physical phenomena such as ambient temperature, humidity, etc. In addition, it is impractical to use smartphones for conducting long-term, outdoor recordings or taking measurements in harsh environments.

Dedicated sensor toolkits can target such harsh environments. The PocketLab [29] consists of wireless sensors, which connect to the student's laptop or mobile. Several example lessons and science kits provide an introduction to the system. The main interface consists of a notebook with a live display and a capture tool for time-series data. These notebooks can be edited by the teacher to provide feedback and guidance on the learning material. However, the learning material within the system is static and does not support any type of interactivity when a student is engaged in an experiment. Similarly, Globisens' Labdisc provides access to raw sensor data [10]. Data can be captured, visualised, and stored but limited interaction is supported by the device. Both of the previous two systems are focused exclusively on physics. In the domain of computer science, the BBC micro:bit [1] is designed to promote "computational thinking" [7] and increase computer literacy [27]. It supports different coding environments (including block-based programming with Scratch [25]) and offers real-time data display. It allows the creation of interactive elements that respond to sensor inputs and is most aligned with the goals of our work. However, we focus on supporting scientific inquiry for school children using sensor-based interactive worksheets through seamless integration of hypothesis testing with analysis, visualisation, storage, and interpretation of the sensor data.

3 INTERACTIVE PLATFORM

In this section, we describe the platform we have developed to support scientific inquiry through sensor-based interactive worksheets. We present three primary design goals for the platform, and we organise our description of the tool around these. To begin, we very briefly outline the process we followed to elicit design requirements from both students and teachers.

3.1 Design Requirements

We began by conducting a series of semi-structured interviews with 9 teachers, focusing on how they normally conduct their science lessons. In total, we recorded 2 hours of interview audio which we transcribed to text prior to analysis. This data revealed that all teachers were familiar with the concept of Predict-Observe-Explain (POE) as a teaching strategy and that they would value a tight integration between our platform and their curriculum. In parallel, we ran observation sessions with 4 student groups to understand how students would interact with worksheets that contained sensor data. In particular, students were shown a range of prototypes where the designs varied in the level of integration between the interfaces for collecting the sensor data and interacting with it. We collected a total of 6 pages of observation notes from these group sessions. The observations supported theoretical considerations from Cognitive Load Theory [30] which suggest that interactions with the measured sensor data should be as direct as possible. One of our designs presented quiz-based interactions, where the questions are answered based upon the sensor input, and we found that this format best maintained students' attention on the lesson. Integrating the instructional content (presented as quizzes) directly with the sensor data mitigates the Coherence Effect, reduces cognitive load, and puts students, who are learning something new, into a guided state of facilitated learning [6].

Based on these observations, we identified three primary design goals. We now describe our platform with respect to these goals: supporting scientific inquiry, scaffolding the learning experience, and engagement through sensor-based interaction.

3.1.1 Supporting Scientific Inquiry: The Predict-Observe-Explain (POE) strategy [3] is a very popular way to teach scientific inquiry. Following this strategy, students learn to split their inquiries into three cyclic phases: predict, observe, and explain [33]. Our platform facilitates each of these phases seamlessly and allows each phase to be supported by different interaction tools. Two steps that typically precede the prediction phase, analysing related work and forming research questions, both require input from the teacher and are not the focus of our platform.

The *prediction* phase involves forming a hypothesis in the context of a given research question. The experiment's variables – typically discrete – are chosen and recorded. For our platform, the physical quantity to be observed is measured with an electronic sensor. Inspired by the H5P toolkit [31], features like drag-and-drop images, drag words, fill-in-blanks, pair/sequence images, and multiple-choice questions are used to allow students to provide answers to their research questions based on the sensor data.

For *observation*, measurements taken from sensors are visualised via a real-time chart using a web UI. The connection between the sensor and the visualisation is seamless – once connected the sensor measurement can be used as an additional input for any interaction (e.g., real-time charts). The students are asked to measure each of the specific variables selected in the preceding step, which provides structure to an otherwise unguided observation. This is one of the key differences from other TEL toolkits, where the learner is only guided on how to use the measurement tool but not how to relate the measurements with the conditions. When there are multiple series of data that need to be visualised, for example, when measuring acceleration and rate-of-turn simultaneously, we opted for displaying only one modality. This avoids possible distractions from having to interpret multiple time-series plots. Multiple independent charts can be displayed by switching cards. One card corresponds to one chart, and cards can be switched by clicking on them, hence only providing the information that is required at a particular point in time.

Finally, the *explanation* phase is supported by reiterating the research question and providing a free-form text entry or audio recorder for capturing notes. The student can be asked whether the captured observation refutes or confirms the hypothesis. The results, since they are connected to the hypothesis, can be structured in a way that allows for direct interpretation of the observations. After students have interpreted and recorded their conclusions a summary of the experiment that can be shared and compared with others is generated.

3.1.2 Scaffolding the Learning Experience: Learners profit from the Segmentation Effect [14], which describes the benefits of being able to self-pace through the learning of single segments, as opposed to being presented with a larger undivided body of content. This is similar to the goal of *"seamless switching between multiple learning tasks"* [34] from seamless mobile learning. Our platform supports this self-pacing, and the selection of single segments, using a slide-based navigation. Only one specific task is visible at a given point in time.

Segments that contain an interaction are guarded until the students have entered their answers, but they can always go back to a previous segment to change their answers. This allows them to review previously seen material and to spend time to understand the material. This also integrates the learning material (e.g., information about the current experiment), interactions (e.g., forming a hypothesis via drag-and-drop images), and real-time sensor measurements.

3.1.3 Engagement Through Sensor-Based Interaction: Digital storytelling has been shown to greatly enhance the engagement of learners [26], and this was supported by feedback from our group observations with students. Through the direct integration of sensor data, it is possible to connect story elements with the physical phenomena under investigation. In our platform, we designed a virtual character that plays the role of the storyteller in the experiment and that can react in real-time to the currently measured values. Such an interactive story may improve the engagement of students, as the sensor measurements are directly experienced by the character rather than being rendered in a more abstract way. Related research from educational studies in computing have shown that personifying the feedback produced by a tool in this way can have a significant impact on both motivation and learning success [18].

3.2 Implementation

To evaluate the platform and address our previously stated research question, we implemented an experiment for use in a real classroom. This experiment was developed with the help of several science teachers, and targeted existing curricula. The experiment involves a virtual alien called Zally, who has different sensitivity levels for ultra-violet (UV) light (measured in UV index) and visible light (measured in lux) due to different conditions on their home-planet. With the help of a digital light sensor, students are to determine Zally's sensitivity levels and identify materials that provide adequate protection for them. Six different materials are provided: clear plastic, red paper, green cellophane, a paper napkin, baking paper, and clear plastic with sunblock. The measurement setup (see Fig. 1b) allowed children in a science classroom to perform the experiment. We will refer to this experiment as the "UV experiment" in subsequent sections of the paper. For the purpose of this experiment, we used a USB UV sensor that can detect and measure UV light and visible light at the same time.

4 EVALUATION

4.1 Participants & Procedure

A total of 42 students (29 boys, 13 girls) from two grade 8 classes (aged 11 to 12) were recruited together with two teachers (both female, each leading a class). Twenty seven students were from a private boys' school, and 15 students (2 boys, 13 girls) from a co-educational public school. The teacher of the private school class had 20 years of teaching experience with secondary training including science expertise. The public school teacher is a generalist with expertise in teaching reading, writing and mathematics but with a self-reported lack of confidence in teaching science. In both classes, students spend two hours per week on topics from the science curriculum.

The study was conducted as part of a usual science class and took about 1.5 hours (see Fig. 1a). At the beginning of the class, the teacher led a review of what the students had recently learned about UV. After that, the teacher played the introduction video of the UV experiment and informed the students to follow the on-screen instructions. Each student was provided with an experiment kit that includes a UV sensor, a micro-USB cable, and different test materials. Students used their personal or school-provided laptop to access the web application.

The first screen of the platform has a video that instructs students about the set-up and sensor connection. When the sensor is successfully connected, students can see the sensor data and familiarise themselves with the sensor. Once the experiment is started, students select two materials out of the six provided that they wish to test. Students indicate their prediction of how well the selected materials will protect Zally by placing the material elements into respective labelled areas (low or high protection). Then, the students are presented with an automatically-generated hypothesis based on their material selection and their prediction. After confirmation, the students are guided through the process of testing the selected material and collecting data accordingly. They collect three sets of data when the sensor is uncovered to create a baseline, then test the experimental materials and collect three sets of data for each. After the data collection for both materials, the previous hypothesis and the collected data are displayed together, and students answer a series of questions to review their results and hypothesis (see Fig. 2).

Upon completing the experiment, students were given an opportunity to go outdoors to undertake free exploration (see Fig. 1d). At the end of the session, students were asked to submit their feedback on the experiment and system using an online form. The feedback form prompted students to answer the following two items: 1) *Things I liked about today's session*, and 2) *Things I would change about today's session.* Lastly, we conducted an interview session with the teachers to collect their feedback.

4.2 Results

4.2.1 Feedback from Students: We received feedback from 34 students: 23 from the private boys' high school and 11 from the public high school. Four students from the private school forgot to submit the form at the end of the session. Four students from the public school had technical problems with their laptops, and were paired with other students and filled in the feedback form as a group.

To analyse this data, we followed the general guidelines for thematic analysis described by Braun and Clarke [4], beginning with data familiarisation. We initially read all responses, and then one researcher assigned codes to each response, synthesizing these into main themes. Another researcher reviewed the themes, codes and comments, and then defined the final key themes. In presenting our findings, we report the main themes under the corresponding survey items.

Things I liked: Students enjoyed learning science using our platform and through its interactions and found it interesting and novel compared to their usual science classes. Many students liked the

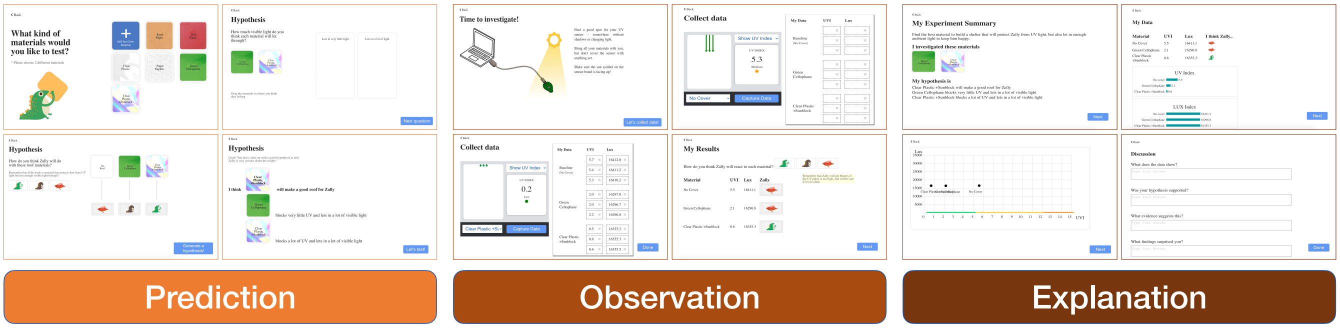

Figure 2: Screenshots showing each stage of the interactive process in our platform. Sensor measurements are integrated directly into the slides and updated in real-time.

experiment and thought it was *fun* (29 comments), with one commenting: *"I liked doing something fun in science for once"*.

Students also appreciated the autonomy they had when using our platform. Three students commented that they liked being able to do the experiment on their own and that they were free to test the materials they wanted. Learning was a common theme in our data, with 8 students commenting that they enjoyed learning new things about UV from the instructional material and through conducting the experiment itself.

Students commented on the scaffolded-learning structure and the seamless approach for performing the experiment. They mentioned in their feedback that the lesson was well-planned and guided them well (5 comments). One student wrote: *"I liked the step by step process"*, and others found that the steps were straightforward and instructions (on the website) were helpful.

The final theme related to the interesting backstory of having to protect Zally (17 comments). One student mentioned the value of relating the experiment to the real-world: *"The fun backstory/reason behind the experiment that helped me understand the real world application of the experiment"*.

Things I would change: Students wanted to investigate beyond the given experiment, and to have a chance for interaction and discussion with other students. Many of the students wanted to test more materials and to test multiple materials at once (10 comments). Everyday wearable apparel, like clothes, sunglasses and hats, were commonly mentioned. Several students wished to test different varieties of sunblock lotion for their UV protection (6 comments), and to do so using natural light outside rather than the lamps provided for the experiment. A desire to have additional virtual characters to play with was also common (8 comments).

The inquiry aspect appeared to spark interest in many students to learn more. Some students specifically stated wanting to better understand UV and lux (3 comments). Others expressed an interest in measuring UV light levels emitted from electronic devices and light sources in the house (6 comments), as well as testing UV light levels at different times of the day, locations and weather conditions (5 comments).

4.2.2 Feedback from Teachers: We now explore feedback from the teachers collected during the post-session interviews. Both teachers discussed the impact that our platform could have on their existing science curriculum and how they might use it. They were pleased that the sensors worked well and looked forward to using other sensors. The public school teacher explained, *"I will spend three or four lessons working on UV, including the importance of sunscreen, skin cancer and fluorescence. Having a device, in any subject, would increase the opportunity to include more practical work on specific topics. These also will allow more student driven practicals, as each would have the device to use to test their own ideas."*. The public school teacher indicated they would use it for a few weeks in a school-term for a relevant topic, and in science extensions or project based learning. Furthermore, the teachers had confidence in using our platform as part of extra-curricular science learning. This is seen from both the private school teacher's comment, *"Once the boys had been shown how to use the device I would be happy for them to use them on their own."* and from the public school teacher's comment, *"With appropriate instructions this work could be done at home [once it's tested in school first]"*. The public school teacher supported the idea of letting students use it at home as she felt that *"Doing the work at home would allow them to share this with their parents as well"*.

The teachers also talked about what they would change if they were to use our platform in practice. The private school teacher told us, *"I feel with a lower ability group it might be useful to have a more structured instruction time (go through the steps in more detail - slide show to show this)"*. The public school teacher commented, *"I would give them specific problems to find the answers for, if I was to use it in more lessons."* The public school teacher hoped to use sensors which could measure carbon dioxide exhaled and oxygen concentration in parallel to body temperature and heart rate. They also suggested making our platform available on different devices such as a smartphone or a tablet.

4.2.3 Observations: We collected a total of 3.5 hours of video footage from the classroom observation and 10 pages of observation notes. We coded the video content and observation notes and focused on engagement and distractions. When students first had the chance to try the UV light sensor before starting the experiment, they were excited by seeing the change. We observed 11 students leave their seats and walk around the classroom with the sensor, to check the readings in different places. Once proceeding to the experiment stage, all the students were mostly focused on reading and following the instructions. Some worked collaboratively, and planned to test different materials and share their results.

After completing the experiment, several students asked whether they could continue outdoors and test their own materials. One group of students self-organised to play a game of "Who can find the strongest UV reading", and another sat in the garden and tested different materials using direct sunlight.

4.3 Discussion

We now return to our research question, and discuss students' perceptions of the guided scientific inquiry lesson. We examine how these were influenced by the integration of the measurement interface and the learning material in our tool, and we present insights that will guide future research.

Step by step navigation helped students learn: The POE strategy consists of three main steps. We divided each step into several substeps and provided interactive slides for easier navigation through each step. For example, we divided the process of hypothesis formulation into three steps. The first step is to identify the controlled variables and dependent variables in the experiment; the second step is to make assumptions about the relationship between the controlled variable and the dependent variable, and the third step is to make assumptions about the overall results of the experiment based on the second step. All the students in our study successfully followed these steps and understood the hypothesis derived from the platform. For example, *"Once you got onto the platform, all the steps were straight forward"*, *"The great step by step process that let me walk my way through the course."*

The virtual character helped students engage by creating empathy: In our platform, we created a virtual character called Zally to connect the UV experiment with a story and a goal. The student's main goal was to protect Zally from UV. This personification indirectly helped students understand the real-world applicability of scientific inquiry. For example, *"It was a fun experiment to test UV light and light. It showed us what materials would protect our little friend Zally best from UV light."*. Most importantly, many students showed empathy toward Zally. For example, *"I'm really happy that I found Zally could survive with Green Cellophane"*. This emotional link with the character in the lesson may have helped students focus, resulting in a better understanding of the underlying theory behind blocking UV. This is evidenced by comments that illustrate a desire to shield the character from UV: *"I found that green cellophane is a better roof for Zally compared to red paper"*. Prior research has also shown the value of building emotional connections for achieving learning outcomes [28]. The use of virtual characters in similar contexts may be an effective way to achieve this.

Sensor-based interaction motivated further exploration and peer discussion: After completing the in-class lesson with our platform, the sensors remained with students for another 30-45 minutes. During this time, students continued their explorations while interacting with each other. They began exploring how other materials can block UV, such as leaves, flowers, rocks, clothes, glasses, and hats. Several students asked to take the sensors home in order to test their sunblock's efficiency in blocking UV. These observations provide some evidence that students were intrinsically motivated by the sensor technology, and keen to apply what they had learned in novel ways. Most importantly, students were keen to compare their results with one another. This was evidenced by a variety of discussions about the UV blocking capability of different materials in the environment. For example, *"UV drops to 0.5 with my glasses! Can you imagine that?"*, *"Really? I tried leaves and I still got 2"*.

5 LIMITATIONS AND FUTURE WORK

In this paper, we evaluated the use of our platform in two classrooms using a single experiment related to measuring UV. Future research is needed to explore other kinds of sensors and how our platform can be applied to different science lessons in other fields. Teachers want to have control of the specific lessons for their students, thus we note that future iterations must be customisable and allow teachers to build experiments to suit their needs. We plan to develop a platform for teachers that will provide this customisation.

Students have limited access to resources since not all schools are outfitted with one laptop per student. This limits the applicability of our approach, which assumes that each child has their own laptop. Furthermore, our approach currently depends on an active internet connection to download the lesson's material, which limits its usage in outdoor scenarios. Integration with mobile or personal devices would alleviate this situation. Since our implementation is based on web standards, we envision only limited challenges for such a transition.

Although we were unable to include a control group in our evaluation who did not use the tool, students viewed the activity positively in comparison to their typical science lessons. We acknowledge that some of the described effects may be due to the novelty of our platform, and not due to our chosen sensor-enriched, interactive worksheet approach. We may find that students are less positive towards using the platform if they were to use it over a longer period of time, with different sensors or lessons. To mitigate this, we plan to design future lessons so they are not overly prescriptive, to give students the freedom to investigate the physical phenomena under consideration on their own.

6 CONCLUSION

Current sensor-based TEL toolkits for supporting science experiments and inquiry require learners to switch their attention between the worksheet and the sensor data recording tool, increasing cognitive load and affecting the learning process. Our platform provides seamless integration of the interactive worksheets with the sensor measurements. In an evaluation involving two classrooms and 42 students, we found that the interactive learning experience provided by our platform was engaging, educational and inspired follow-up experiments to be conducted.

7 SELECTION AND PARTICIPATION OF CHILDREN

A total of 42 students (29 boys, 13 girls) from two grade 8 classes (aged 11 to 12) were recruited together with two teachers (both female, each leading a class). Twenty seven students were from a private boys' school, and 15 students (2 boys, 13 girls) from a co-educational public school. Prior to the study, ethical approval was obtained from the Human Participants Ethics Committee of the University of Auckland (UAHPEC 024519). Participation consent was received from the students' parents and from the teachers.

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